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(54) Title: BIODEGRADABLE POLYMER MATRICES FOR SUSTAINED DELIVERY OF LOCAL ANESTHETIC AGENTS

(57) Abstract

An improved biodegradable controlled release system consisting of a polymeric matrix incorporating a local anesthetic for the prolonged administration of the local anesthetic agent, and a method for the manufacture thereof, are disclosed. The polymers and method of manufacture used to form the PLAMs are selected on the basis of their degradation profiles: release of the topical anesthetic in a linear, controlled manner over a period of preferably two weeks and degradation *in vivo* with a half-life of less than six months, more preferably two weeks, to avoid localized inflammation. Alternatively, a non-inflammatory can be incorporated into the polymer with the local anesthetic to prevent inflammation.

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BIODEGRADABLE POLYMER MATRICES FOR SUSTAINED DELIVERY OF LOCAL ANESTHETIC AGENTS

Background of the Invention

The U.S. Government has rights in this invention pursuant to National Institutes of Health Grant No. GM-15904 to Harvard Anesthesia Research and Teaching Center to C. Berde, and Grant No. CA 5257 to R. Langer.

This invention is generally in the field of anesthesiology and, in particular, the delivery of anesthetic agents which locally block pain for periods of time of less than about two weeks.

In order to provide local or regional blockade for extended periods, clinicians currently use local anesthetics administered through a catheter or syringe to a site where the pain is to be blocked. This requires repeated administration where the pain is to be blocked over a period of greater than one day, either as a bolus or through an indwelling catheter connected to an infusion pump. These methods have the disadvantage of potentially causing irreversible damage to nerves or surrounding tissues due to fluctuations in concentration and high levels of anesthetic. In addition, anesthetic administered by these methods are generally neither confined to the target area, nor delivered in a linear, continuous manner. In all cases, analgesia rarely lasts for longer than six to twelve hours, more typically four to six hours. In the case of a pump, the infusion lines are difficult to position and secure, the patient has limited, encumbered mobility and, when the patient is a small child or mentally impaired, may accidentally disengage the pump.

Drugs are typically administered in a variety of ways, including by injection, topical administration, oral ingestion, and sustained release devices. Methods which provide for systemic, rather than localized, delivery are not an option with local anesthetics since these could interfere with the patient's ability to breathe, if administered systemically. Devices could potentially provide for a sustained, controlled, constant localized release for longer periods of time than can be achieved by injection or topical administration. These devices typically consist of a polymeric matrix or liposome from which drug is released by diffusion and/or degradation of the matrix. The release pattern is usually principally determined by the matrix material, as well as by the percent loading, method of manufacture, type of drug being administered and type of device, for example, microsphere. A major advantage of a biodegradable controlled release system over others is that it does not require the surgical removal of the drug depleted device, which is slowly degraded and absorbed by the patient's body, and ultimately cleared along with other soluble metabolic waste products.

Systemic anesthetics such as methoxyflurane, have been incorporated into liposomes and lecithin microdroplets, for example, as described by Haynes, et al., Anesthesiology 63:490-499 (1985). To date, the liposome and lecithin preparations have not been widely applied in clinical or laboratory practice, because of their inability to provide dense blockade for a prolonged period of time (i.e., three or more days) in a safe and controlled manner. The lecithin microdroplets and liposomes degrade or are phagocytized too rapidly, in a matter of hours.

Other lipid based devices, formed in combination with polymer, for release of local anesthetics are described by U.S. Patent No. 5,188,837 to Domb.

Local anesthetics have been incorporated into biodegradable polymeric devices, for example, polylactic acid microspheres, as described by Wakiyama, et al., Chem. Pharm. Bull., 30:3719-3727 (1982). In contrast to the lipid based materials, the poly(lactic acid) devices take over a year to degrade and cause localized inflammation. Berde, et al., Abstracts of Scientific Papers, 1990 Annual Meeting, Amer. Soc. Anesthesiologists, 73:A776 (Sept. 1990), reported the use of a device formed of a polyanhydride polymer matrix of copolymer 1,3 bis (p-carboxyphenoxy)propane and sebacic acid, in a ratio of 1:4, into which dibucaine free base was incorporated by compression molding. This drug-polymer device, however, had several drawbacks. For example, because the drug was incorporated into the polymer matrix by compression molding, the device sometimes displayed bulk erosion, causing fast initial release of drug. In addition, the device often generated an inflammatory response or a capsule of serous material or fibrin, which is particularly a problem when located adjacent to nerves.

Accordingly, it is the object of this invention to provide an improved biodegradable controlled release device which administers local anesthetic for a prolonged period of time in a substantially constant, linear fashion and which provokes minimal encapsulation and/or other immune responses.

It is a further object of the present invention to provide a method and means for modulating the rate of release of the local anesthetic from the bioerodible polymer matrix.

Summary of the Invention

An improved biodegradable controlled release device for the prolonged administration of a local anesthetic agent, and a method for the manufacture thereof are disclosed. The device is formed of a biodegradable polymer degrading significantly within a month, with at least 50% of the polymer degrading into non-toxic residues which are removed by the body within a two week period. Useful polymers include polyanhydrides, polylactic acid-glycolic acid copolymers and polyorthoesters containing a catalyst. Local anesthetics are incorporated into the polymer using a method that yields a uniform dispersion, such as melt casting or spray drying, not compression molding. Local inflammatory responses against the polymeric devices are avoided through selection of the polymer, repeated recrystallization of the monomers forming the polymer and resulting polymers to remove impurities, monomer and degradation products, the method of incorporation of the anesthetic and in some embodiments, by inclusion of an antiinflammatory such as dexamethasone, either within the polymer or implanted with the polymer. The device can be formed as slabs, films, microparticles, including microspheres, or a paste.

The type of anesthetic and the quantity are selected based on the known pharmaceutical properties of these compounds. It has been discovered that bupivacaine is a better anesthetic agent for use in polymeric devices than other local anesthetics such as dibucaine. It has also been determined that salts of the anesthetic agents (e.g., hydrochlorides, bromides, acetates, citrates, sulfates, etc.) yield better results when

incorporated into polymeric devices than the free base forms.

It is possible to tailor a device to deliver a specified initial dosage and subsequent maintenance dose by manipulating the percent drug incorporated, the form of local anesthetic, for example, more hydrophobic free base versus more hydrophilic hydrochloride, the method of production, and the shape of the matrix.

The polymeric devices are implanted at the site where the anesthetic is to be released. This can be at the time of surgery, prior to or at the time of injection, especially when the device is in the form of microparticles, or following removal of systemic anesthetic.

Examples demonstrate the superiority of making the polymeric device using a method resulting in uniform dispersion of anesthetic in the device and prevention of inflammation by incorporation of an antiinflammatory with the anesthetic-polymeric device. The device delivers the local anesthetic at rates above 3.5 mg/day for up to four days or more with substantially zero order kinetics, i.e., linear release. The effectiveness of these devices *in vivo* is also demonstrated. Using a rat sciatic nerve *in vivo* model, it was shown that the devices provide degrees of sensory blockade for up to five to six days and motor blockade for up to three days. The blockade appeared reversible, with complete recovery of strength and sensation.

The examples also demonstrate the effect of cis-hydroxyproline and dexamethasone on inflammation, encapsulation and duration of sensory and motor blockade following implantation of bupivacaine 20% CPP:SA (20:80) polymer matrices along the sciatic nerves of rats. Cis-

hydroxyproline (CHP) did not diminish encapsulation and did not alter the duration of sensory or motor blockade. In contrast, dexamethasone (DMS) produced significant reductions in encapsulation and inflammation, and was associated with more prolonged sensory analgesia. These effects were not mediated by systemic concentrations of dexamethasone, since unilateral incorporation of DMS into PLAM did not diminish encapsulation around contralateral control implants that did not receive DMS. DMS was effective in inhibiting an anti-inflammatory response and preventing encapsulation of the polymeric device in rats at doses from 45 μg to 180 μg, administered in three pellets containing between 15 μg and 60 μg DMS/pellet. The preferred dosage is 60 μg anti-inflammatory/kg body weight, which is equivalent to a dosage range of between 20 μg/kg body weight, and 1 mg/kg body weight. These doses did not produce suppression of glucocorticoid secretion.

Brief Description of the Drawings

Figures 1a and 1b are graphs of the percent cumulative release of bupivacaine HCl (Figure 1a) and dibucaine HCl (Figure 1b) as a function of time in days, comparing release from hot melt molded devices with release from compression molded devices formed of 1,3 bis (p-carboxyphenoxy)propane:sebacic acid (CPP:SA) (1:4).

Figure 2 is a graph of *in vitro* polymeric pellet release studies, percent cumulative release over time in days of 12% bupivacaine HCl in 10 ml PBS (dark circles); 20% bupivacaine HCl in 25 ml PBS (open triangles); 20% bupivacaine 10 ml PBS (dark squares); and 20% bupivacaine in 2 ml PBS (open square).

Figures 3a-3f are graphs of the results of nerve block assays: Figure 3a is a graph of the number of rats over days post-implantation showing dense, partial or no block pain relief; Figure 3b is a graph of latency in seconds over days post-implantation for G1 devices (dark squares) and control (open squares); Figure 3c is a graph of the number of rats showing dense, partial or no block pain relief over days post-implantation; Figure 3d is a graph of latency in seconds over days post-implantation for G2 devices (dark circles) and control (open circles); Figure 3e is a graph of the number of rats showing dense, partial or no block pain relief over days post-implantation; and Figure 3f is a graph of latency in seconds over days post-implantation for G3 devices (dark circles) and control (open circles). The data represent mean ± S.E.M. *Denotes $p<0.05$ significance (†, $p=0.07$).

Figure 4 is an autoradiogram of Northern blot analyses for five different rats receiving polymeric implants. This is an image of Northern autoradiograms that were digitized with an optical scanner for display and quantification. Radiolabeled probes were used to measure mRNA levels encoding substance P (preprotachykinin) extracted from DRG tissue (L4-6) corresponding to the sciatic nerves. The mean grayscale density of autoradiogram signal bands was determined by averaging the values of image pixels corresponding to specific RNA-probe hybridizations. Preprotachykinin (PPT) mRNA levels were normalized to 28S rRNA levels as a measure of total RNA loaded. Cervical DRG tissue (C3-5) was used as an additional non-operated control. N = Non; B= Bupivacaine' L = Lumbar' C = Cervical.

Figure 5 is a graph of latency in seconds versus hours post-implantation for groups 4

(squares), 5 (diamonds), 6 (circles) and control (triangles) rats treated with PLAMs containing anesthetic and antiinflammatory.

Figures 6a, b, and c are graphs of number of PLAM treated rats versus hours post-implantation who showed severe impairment (dark bars), partial impairment (stripes), and no motor block (open bars).

Figure 7 are graphs of latency in seconds versus hours post-implantation for groups 1 (squares), 2 (diamonds), 3 (circles) and control (triangles) rats treated with PLAMs containing anesthetic and antiinflammatory.

Figures 8a, 8b, and 8c are graphs of number of PLAM treated rats versus hours post-implantation who showed severe impairment (dark bars), partial impairment (stripes), and no motor block (open bars).

Detailed Description of the Invention

Systems for the controlled and prolonged delivery of a local anesthetic agent to a targeted area are provided. These systems can be used for the management of various forms of persistent pain, such as postoperative pain, sympathetically maintained pain, or certain forms of chronic pain such as the pain associated with many types of cancer.

Polymers

It is important that the polymer degrade *in vivo* over a period of less than a year, with at least 50% of the polymer degrading within six months or less. More preferably, the polymer will degrade significantly within a month, with at least 50% of the polymer degrading into non-toxic residues which are removed by the body, and 100% of

the drug being released within a two week period. Polymers should also degrade by hydrolysis by surface erosion, rather than by bulk erosion, so that release is not only sustained but also linear. Polymers which meet this criteria include some of the polyanhydrides, co-polymers of lactic acid and glycolic acid wherein the weight ratio of lactic acid to glycolic acid is no more than 4:1 (i.e., 80% or less lactic acid to 20% or more glycolic acid by weight), and polyorthoesters containing a catalyst or degradation enhancing compound, for example, containing at least 1% by weight anhydride catalyst such as maleic anhydride. Other polymers include protein polymers such as gelatin and fibrin and polysaccharides such as hyaluronic acid. Polylactic acid is not useful since it takes at least one year to degrade *in vivo*.

The polymers should be biocompatible. Biocompatibility is enhanced by recrystallization of either the monomers forming the polymer and/or the polymer using standard techniques.

Anesthetics

The systems employ biodegradable polymer matrices which provide controlled release of local anesthetics. As used herein, the term "local anesthetic" means a drug which provides local numbness or pain relief. A number of different local anesthetics can be used, including dibucaine, bupivacaine, etidocaine, tetracaine, lidocaine, and xylocaine. The preferred anesthetic is bupivacaine or dibucaine, most preferably in the form of a salt, for example, the hydrochloride, bromide, acetate, citrate, or sulfate. Compared to the free base form of these drugs, the more hydrophilic hydrochloride salt displays longer and denser nerve block, more complete release from polymer matrices, slower clearance from the targeted nerve area, and

less encapsulation. Bupivacaine is a particularly long acting and potent local anesthetic when incorporated into a PLAM. Its other advantages include sufficient sensory anesthesia without significant motor blockage, lower toxicity, and wide availability.

The devices can also be used to administer local anesthetics that produce modality-specific blockade, as reported by Schneider, et al., Anesthesiology, 74:270-281 (1991), or that possess physical-chemical attributes that make them more useful for sustained release then for single injection blockade, as reported by Masters, et al., Soc. Neurosci. Abstr., 18:200 (1992), the teachings of which are incorporated herein.

The anesthetic is incorporated into the polymer in a percent loading of 0.1% to 70% by weight, preferably 5% to 50% by weight. It is possible to tailor a system to deliver a specified loading and subsequent maintenance dose by manipulating the percent drug incorporated in the polymer and the shape of the matrix, in addition to the form of local anesthetic (free base versus salt) and the method of production. The amount of drug released per day increases proportionately with the percentage of drug incorporated into the matrix (for example, from 5 to 10 to 20%). In the preferred embodiment, polymer matrices with not more than about 30% drug incorporated are utilized, although it is possible to incorporate substantially more drug, depending on the drug, the method used for making and loading the device, and the polymer.

Antiinflammatories

Antiinflammatories that are useful include steroids such as dexamethasone, cortisone, prednisone, and others routinely administered

orally or by injection. Useful loadings are from 1 to 30% by weight. The preferred dosage is 60 μg anti-inflammatory/kg body weight, which is equivalent to a dosage range of between 20 μg/kg body weight, and 1 mg/kg body weight.

The following examples demonstrate that polymers alone and when combined with local anesthetics generate a substantial encapsulation response within two weeks of placement in rats. The encapsulation response to polymer containing local anesthetic is worse than the polymer alone. This encapsulation is a natural response to a foreign body and occurs at varying rates with many substances commonly regarded as "biocompatible". Minimization of the encapsulation response is important for proper healing, for avoidance of unsightly scars, for optimal access of drug to its site of action, and potentially to decrease the likelihood of infection.

Encapsulation involves formation of a fibrous material around foreign bodies. It begins with attempts by granulocytes to phagocytose and incorporate the foreign material during the initial acute inflammatory response. The process of encapsulation through fibrosis is due to histiocytes and fibroblasts, which generate the layers of collagenous connective tissue surrounding the implant. Encapsulation depends upon several factors, including the chemical and physical characteristics of the implant, the mechanical action of the implant, its site in the body and the presence of microorganisms.

The examples demonstrate that dexamethasone reduces encapsulation, does not reduce the intensity of the nerve block generated by the release of anesthetic from the polymer, does not affect the recovery of sensation and strength, and

works only locally due to the low doses which are effective, and therefore exerts no effect on the normal pituitary-adrenal hormone responses.

Methods of Manufacture

The polymeric devices are preferably manufactured using a method that evenly disperses the anesthetic throughout the device, such as solvent casting, spray drying or hot melt, rather than a method such as compression molding. As shown by Example 1, in contrast to compression molded tablets, which sometimes display bulk erosion and fast initial release of drug, hot melt molded tablets have denser and more homogenous matrices, causing them to release drug in a more safe and linear fashion.

The form of the polymeric matrix is also important. Devices can be shaped as slabs, beads, pellets, microparticles, including microspheres and microcapsules, or formed into a paste. Microparticles, microspheres, and microcapsules are collectively referred to herein as "microparticles". The device can be coated with another polymer or other material to alter release characteristics or enhance biocompatibility. The microparticles can be administered as a suspension or as a device within a gelatin capsule, or used to form a paste, for example.

In the preferred embodiments, the device will be in the form of microparticles. A desired release profile can be achieved by using a mixture of microparticles formed of polymers having different release rates, for example, polymers releasing in one day, three days, and one week, so that linear release is achieved even when each polymer *per se* does not release linearly over the same time period.

Methods of Administration

In the preferred method of administration, the devices are microparticles and are administered by injection at the site where pain relief is to be achieved. Alternatively, the device is surgically implanted at the site. The pellets may be injected through a trochar, or the pellets or slabs may be surgically placed adjacent to nerves.

Potential applications include two to five day intercostal blockade for thoracotomy, or longer term intercostal blockade for thoracic post-therapeutic neuralgia, lumbar sympathetic blockade for reflex sympathetic dystrophy, or three-day ilioinguinal/iliohypogastric blockade for hernia repair.

The present invention is further described with reference to the following non-limiting examples.

Example 1: Preparation of Polymer Matrices for Sustained Release of Bupivacaine HCL.

Monomers of CPP and SA (20:80) were converted to mixed anhydrides after a 30 minute reflux in acetic anhydride. The prepolymers were then recrystallized over several weeks in a mixed solvent of acetic anhydride and dimethylformamide, followed by polycondensation under nitrogen sweep. The resulting polymers were then ground to a fine powder and mixed with crystalline Bupivacaine HCL (20% ± 2% drug by dry weight). Cylindrical pellets were then produced by placing a tuberculin syringe filled with drug-polymer mixture in a dry oven at 115°C for 15-20 min. and then injecting the molten solid into teflon tubing (3.2 mm i.d.) or by compression of the polymer powder.

Release of bupivacaine from the device was measured in phosphate buffer, pH 7.4, over a period of 10 days. The results comparing release from compression molded-tablets and hot melt-pellets are

shown in Figures 1a. Significantly more linear release was obtained with devices prepared by hot melt.

Example 2: Preparation of Polymer Matrices for Sustained Release of Dibucaine.

Polymer-drug matrices were prepared as detailed above, substituting crystalline dibucaine HCl for bupivacaine HCl. Release of dibucaine from matrices was then measured in phosphate buffer, pH 7.4, over a period of 10 days. The results comparing release from compression molded-tablets and hot melt-pellets are shown in Figure 1b. The same release profiles were observed.

Example 3: Prolonged regional nerve blockade by controlled release of local anesthetic from a biodegradable polymeric matrix.

Cylindrical pellets made from polymer matrices incorporated with bupivacaine-HCl were implanted surgically along the sciatic nerves of rats *in vivo*. Sensory and motor blockade was produced for periods ranging from two to six days. Contralateral control legs receiving polymer implants without drug showed no block. Blockade was reversible, and animals appeared to recover sensory and motor function normally. Biochemical indices of nerve and muscle function were indistinguishable from contralateral controls. This biodegradable polymer system provides a promising new alternative for the delivery of local anesthetics to peripheral nerves to produce prolonged blockage for the management of acute and chronic pain.

METHODS AND MATERIALS

PLAM Implants

Biodegradable polymeric pellets were formed from a polymer mixture, 20% poly[bis(p-carboxyphenoxy) propane anhydride] (poly CPP) and 80% sebacic acid (SA), impregnated with crystalline

bupivacaine·HCl, to release this local anesthetic in a controlled manner. Polymer-local anesthetic matrix (PLAM) pellets were made by mixing 150 μm sieved crystals of bupivacaine-HCl at 12% and 20% with polymer powder. In brief, cylindrical pellets were produced by melting the mixtures in a tuberculin syringe at 115°C in a dry oven and then injecting the molten mixture into Teflon tubing (3.2 or 4.8 mm i.d.). After cooling, the pellets were cut to specified lengths and weights. Control pellets were made in an identical manner using polymer without drug.

Three sizes of PLAM pellets, loaded to 20% by weight with bupivacaine·HCl, were used as implants to examine dosage effects. Group 1 pellets weighed 50 ± 3 mg and were 4.0 ± 0.3 mm long, 3.1 ± 0.2 mm diameter. Group 2 pellets were twice the length of Group 1 pellets, 100 ± 5 mg, 9.8 ± 2 mm long and 3.1 ± 0.2 diameter. Group 3 pellets weighed 125 ± 5 mg and were 6.0 ± 0.1 mm long, 4.7 ± 0.2 mm diameter. Pellets were sterilized via gamma irradiation for *in vitro* or *in vivo* use. Different batches of PLAM pellets were used and similar results were obtained.

In Vitro

Bupivacaine PLAM pellets (equal in size to Group 2 pellets) loaded with 12% or 20% bupivacaine were immersed in various volumes (2 ml, 10 ml, 25 ml) of phosphate-buffered saline (PBS) with 0.1% sodium azide (pH 7.4 at 37°C). Buffer was collected and replaced at 0.5, 2, 8, 16, 24 hour time points, then once daily thereafter for 3 weeks and stored at -20°C before high performance liquid chromatography (HPLC) assay. Bupivacaine standards, 0.23, 0.46, 0.77, 2.3 μg, analyzed on average after every tenth sample, produced linear response values ($R^2 > 0.995$).

PLAM Implantation

For surgery, male rats (150-250 g Sprague-Dawley) were anesthetized with 50-75 mg/kg pentobarbital (i.p.) for Groups 1 and 2 and halothane for Group 3 (4% in oxygen for induction and 2% for maintenance). The shaved skin of the dorsal thigh was incised midway between the hip and the knee. The hamstring muscles were divided with a small hemostat, exposing the dorsal aspect of the sciatic nerve. Under direct vision, polymer pellets could be easily fitted into a large space between muscle layers surrounding the nerve. The space containing the pellets was bathed with 0.5 cc of an antibiotic solution (5000 units/ml penicillin G sodium and 5000 μg/ml streptomycin sulfate). The fascia overlaying the hamstrings were reapproximated with a single suture before closing skin with two wound clips.

For all rats, PLAM pellets were implanted surgically along the sciatic nerve in the upper thigh, with drug-containing implants on the experimental side and control (drug-free) implants on the contralateral (control) side.

Nerve Block Tests

Motor Block

The rats were behaviorally tested for sensory and motor blockage in a quiet observation room at 24 ± 1°C. PLAM implantation was only performed in rats showing appropriate baseline hot plate latencies after at least one week of testing. In all testing conditions, the experimenter recording the behavior was unaware of the side containing the local anesthetic. To assess motor block, a 4-point scale based on visual observation was devised: (1) normal appearance, (2) intact dorsiflexion of foot with an impaired ability to splay toes when elevated by the tail, (3) toes and

foot remained plantar flexed with no splaying ability, and (4) loss of dorsiflexion, flexion of toes, and impairment of gait. For graphing clarity, partial motor block equals a score of 2 and dense motor block is a score of either 3 or 4.

Sensory Block

Sensory blockade was measured by the time required for each rat to withdraw its hind paw from a 56°C plate (IITC Life Science Instruments, Model 35-D, Woodland Hills, CA). The rats were held with a cloth gently wrapped above their waist to restrain the upper extremities and obstruct vision. The rats were positioned to stand with one hind paw on a hot plate and the other on a room temperature plate. With a computer data collection system (Apple IIe with a footpad switch), latency to withdraw each hind paw to the hot plate was recorded by alternating paws and allowing at least fifteen seconds of recovery between each measurement. If no withdrawal occurred from the hot plate within 15 seconds for Groups 1 and 2 or 12 sec for Group 3, the trial was terminated to prevent injury and the termination time was recorded. Testing ended after five measurements per side, the high and low points were disregarded, and the mean of the remaining three points was calculated for each side. Animals were handled in accordance with institutional, state and federal guidelines.

Necropsy

The animals were sacrificed two weeks after implantation, approximately one week after they all returned to baseline levels in motor and sensory tests. *In vitro* approximations predict drug depletion (<5% left) from the polymer matrix by one week, corresponding well with the observed block. Thus, the sciatic nerve was free of local

anesthetic for approximately one week before post-mortem analyses.

Histology

Sections of sciatic nerve approximately 2-3 cm in length, adjacent and proximal to the implants, were preserved in 10% formalin solution (24 mM sodium phosphate, pH 7). Sections were then embedded in paraffin, stained with hematoxylin and eosin, and examined by light microscopy.

Plasma Analysis

Five rats (250-275 g), anesthetized with ketamine-HCl (100 mg/ml at 1.5 ml/kg, i.p.) and xylazine (4 mg/ml at 4 mg/kg, i.p.), were implanted with a silastic catheter into the right jugular vein. Two days after the catheters were implanted, Group 1 pellets loaded with 20% bupivacaine (300 mg) were implanted next to the sciatic nerve. Blood was withdrawn (0.5 cc) before implantation and 1, 4, 24, 48, 72, and 96 hours after PLAM implantation via the indwelling central venous cannulae. Plasma was extracted with an equal volume of HPLC grade methanol (Fischer Scientific, Pittsburgh, PA), centrifuged (10,000 x g) and the methanol phase filtered (0.2 μm nylon syringe type, Rainin, Woburn, MA) prior to HPLC analysis. The HPLC reliably quantified bupivacaine concentrations in the plasma methanol extraction phase down to 10 ng/ml. The bupivacaine standards used for blood plasma analyses were added to plasma aliquots prior to methanol extraction. The peak matching the standard bupivacaine peak's retention time was verified in plasma samples by doping with bupivacaine.

Biochemical Assays

Acetylcholine Receptor

The gastrocnemius muscle was excised from rats that had received group 2 implants and assayed

for I_{125} alpha-bungarotoxin binding as described by Martyn et al., Anesthesiology 76:822-843, 1992; and Masters et al. Meeting for the American Society of Anesthesiologists 75:A680, 1991. Gastrocnemius muscle I^{125} alpha-bungarotoxin binding was used as a measure of acetylcholine receptor number, which up-regulate (increase) in response to denervation.

Substance P and its Encoding mRNA

Ganglia were excised from cervical (C3-5) and lumbar (L4-6) regions, immediately frozen on dry ice and homogenized in a 3 M lithium chloride/5 M urea solution. The spun-down pellets were purified for RNA analysis by the method of Masters, et al., BioTechniques, 12:902-911, 1992, and the supernatants were desalted on C-18 columns for peptide radioimmunoassay (RIA). In the RIA, unlabeled substance P was competed against Bolten-Hunger I^{125} labeled substance P with a polyclonal antibody specific for substance P in duplicate samples, as described by Too H-P, Maggio J: Radioimmunoassay of Tachykinins, Methods in Neurosciences. Edited by Conn PM. New York, Academic Press, 1991, pp 232-247. The assay was sensitive to 5-10 femtomoles/assay tube. Protein levels eluted with substance P were analyzed with a microtiter plate bicinchoninic (BCA) protein assay (Pierce, Rockford, IL).

Northern blot analysis of dorsal root ganglia, able to accurately detect 20% differences in RNA levels in single dorsal root ganglia, was developed as described by Masters (1992). Purified total RNA samples were quantitated with an ethidium bromide Tris-acetate/EDTA gel and equal amounts loaded onto a formaldehyde denatured Northern gel. Relative quantities of messenger RNA encoding for the neuropeptide substance P were normalized to 28S ribosomal RNA (gamma-preprotachykinin/28S rRNA

autoradiography grayscale density). Ethidium bromide photonegatives and hybridization autoradiograms were digitized with a flatbed optical scanner and the resulting image analyzed for grayscale density of the signal bands.

The Northern analysis used a full length cDNA of T-preprotachykinin provided by Dr. J. Krause, Washington University, St. Louis, MO and subcloned into a Promega (Madison, WI) pGEM-3Z riboprobe vector. ^{32}P-UTP labeled riboprobe (specific activity of approximately 10^9 cpm/μg) was made using RNA T7-polymerase (Promega Piscataway, NJ). A 30-mer oligonucleotide sequence, complementary to a region of rat 28S ribosomal RNA (5'-AAUCCUGCUC AGUACGAGAG GAACCGCAGG-3'), was for normalization of total RNA loaded into the electrophoretic gel. Twenty ng of oligonucleotide was ^{32}P end-labeled with the given procedure using T4 polynucleotide kinase (GIBCO BRL; Gaithersburg, MD) and purified on a Nick size exclusion column. The specific activity of the probe was greatly reduced (to approximately 10^5 cpm/μg) by adding 4 μg unlabeled oligonucleotide to the column eluent (400 μl) to reduce the hybridization signal and improve hybridization kinetics.

Statistics

Data were analyzed using linear regression tests, ANOVA, Chi Square tests and Wilcoxon rank-sum tests, where appropriate.

RESULTS

In Vitro Release

HPLC results showed that 96% of the 20 mg of bupivacaine incorporated into a 100 mg PLAM pellet was released within 8 days. Because release rate decreased with time, cumulative release rose toward an asymptote. The cumulative release profile was similar for 12% bupivacaine pellets in

10 ml buffer. Group 2 pellets were found to release approximately 75% of the loaded bupivacaine within 4 days *in vitro*, as shown in Figure 2.

In Vivo Neural Block Measurements

Group 1 implants (295 ± 10 mg total PLAM) in seven animals produced sciatic nerve blockade for periods lasting 2-3 days, as shown in Figure 3a. Dense motor blockade was evident in most animals for two days. Sensory blockade, measured as increased leg-withdrawal latency to heat in comparison to contralateral control leg, was greater than 200% for day 1 and greater than 70%-40% for days 2-3, respectively, as shown in Figure 3b. Group 2 implants (295 ± 10 mg total PLAM) in six animals produced sciatic nerve blockade for a 4 day period, as shown in Figure 3c. Motor blockade was dense for 3-4 days in most animals. Sensory blockade increased leg-withdrawal latency greater than 200% for day 1, greater than 100% for day 2 and 3, and greater than 40% for day 4, as shown by Figure 3d. One of the seven rats receiving a group 2 implant did not recover from the surgical implantation procedure. The animal appeared sluggish and lost weight, and was therefore dropped from the study. Group 3 implants (375 ± 10 mg total PLAM) in six animals produced partial or complete motor blockade for 4 days and sensory blockade for 4-5 days, including leg-withdrawal latencies that increased over 185% for the first 3 days, greater than 100% for day 4 and greater than 30% for day 5, as shown by Figures 3e and 3f. No impairments were observed on the contralateral control side, implanted with an equal mass of polymer pellets without drug. These results indicate that the increased mass of the PLAM implant increases the period of blockade, suggesting a dose-response relationship.

Histology

Sciatic nerve histologic examination showed minimal perineural inflammation with a foreign body response consistent with a local response to previous surgery. Using light microscopy, no evidence of axonal degeneration or demyelination was noted either proximal or distal to the implantation site.

Biochemical Assays

Prolonged release of local anesthetic and polymer degradation near the sciatic nerve did not lead to differences in any of several biochemical comparisons made between the side that received PLAM implants and the contralateral control side, two weeks post-implantation (Table 1). There was no significant difference found in tests for: (1) acetylcholine receptor number in gastrocnemius muscle, (2) the level of substance P, a neuromodulator involved in nociception, in lumbar or cervical dorsal root ganglia, or (3) the level of RNA encoding for substance P, preprotachykinin (PPT), in lumbar dorsal root ganglia, using a novel small-sample Northern blot system, as demonstrated by Figure 4.

TABLE 1: Biochemistry results of animals with PLAM implants, comparing the bupivacaine-treated leg to the contralateral control leg.

Analysis	Bupivacaine-Treated[a] Control[a]
Acetylcholine Receptor in gastrocnemius muscle (femtomole/mg protein)	44.6±1 3.3±2.9*
Substance P content in DRG (femtomole/mg protein)	
Lumbar (n=7)	0.12±01 0.11±01*
Cervical (n=7)	0.08±01 0.07±01*
Substance P mRNA in DRG (PPT/28S rRNA)	
Lumbar (n=5)	1.04±09 1.03±05*
Cervical (n=4_	0.77±10 0.87±21*

[a] (Mean ± S.E.M.)
* p >0.3, Bupivacaine-treated vs control

Plasma Levels

A potential risk of prolonged nerve blockade is systemic accumulation of local anesthetics, leading to convulsion, arrhythmia, and myocardial depression. To examine this risk, plasma concentrations of bupivacaine were measured in five additional rats implanted with Group 1 PLAM pellets (295 ± 5 mg total), at 1, 4, 24, 48, 72 and 96 hours post-implantation. All concentrations were less than 0.1 μg/ml, far below the threshold for toxicity of 305 μg/ml.

In summary, prolonged reversible blockade of the rat sciatic nerve was achieved for periods of 2-6 days *in vivo* using release of bupivacaine from a bioerodable polymer matrix. The implants were well tolerated by the animals, and produced only mild inflammation consistent with the presence of a foreign body. Recovery of motor and sensory function appeared complete.

Example 4: Implantation of PLAMs containing anesthetic in combination with antiinflammatory.

Depending upon the method of preparation, it was common in the previous studies to observe some encapsulation around the PLAM at autopsy two weeks following implantation. Encapsulation involves formation of a fibrous material around foreign bodies. It begins with attempts by granulocytes to phagocytose and incorporate the foreign material during the initial acute inflammatory response. The process of encapsulation through fibrosis is due to histiocytes and fibroblasts, which generate the layers of collagenous connective tissue surrounding the implant. Encapsulation depends upon several factors, including the chemical and physical characteristics of the implant, the mechanical action of the implant, its site in the body and the presence of microorganisms.

The protective function which encapsulation provides may also produce unwanted scarring. An example of this is shown by the studies examining the presence of fibrous capsules around silicon breast implants. Besides forming a large "scar" inside the body, encapsulation may also be a limiting factor in the applicability and usefulness of biodegradable drug delivery systems. Work by Anderson, et al. (J.M. Anderson, H. Niven, J. Pelagalli, L.S. Olanoff, and R.D. Jones, "The role of the fibrous capsule in the function of implanted drug-polymer sustained released systems," J. Biomed. Mater. Res., 15, 889-902 (1981)) has shown that the fibrous capsule which eventually surrounds an implant retards the drug diffusion rate and consequently lowers the local and systemic drug levels. In addition, other studies have shown that the duration of sensory blockade *in vivo* with

bupivacaine impregnated PLAM was less than that expected from the results of PLAMs examined *in vitro*.

A method which reduces encapsulation is therefore needed for two reasons: (1) to diminish the unwanted consequences of "scarring" and (2) to enhance the release behavior of drug-polymer sustained release systems.

In the present study, the effects of dexamethasone and cis-hydroxyproline on inflammation, encapsulation and duration of sensory and motor blockade following implantation of bupivacaine-impregnated polymer matrices along the sciatic nerves of rats have been determined. Each drug has been shown separately in other studies to act upon different components of the inflammatory process. (L. Christenson, L. Wahlberg, and P. Aebischer, "Mast cells and tissue reaction to intraperitoneally implanted polymer capsules," J. Biomed. Mater. Res., 25, 1119-1131 (1991); L. Christenson, P. Aebischer, P. McMillian, and P.M. Galletti, "Tissue reaction to intraperitoneal polymer implants: species difference and effects of corticoid and doxorubicin," J. Biomed. Mater. Res., 23, 705-718 (1989); D. Ingber and J. Folkman, "Inhibition of angiogenesis through modulation of collagen metabolism," Lab. Invest., 59, 44-51 (1988); and J.P. Iannotti, T.C. Baradet, M. Tobin, A. Alavi, and M. Staum, "Synthesis and characterization of magnetically responsive albumin microspheres containing cis-hydroxyproline for scar inhibition," Orthop. Res. Soc., 9, 432-444 (1991)). Their individual effects on reducing encapsulation and improving drug release behavior were examined in this study.

METHODS AND MATERIALS

Implants

Copolymers of 1,3-bis(p-carboxy-phenoxy)propane and sebacic acid (20:80) were synthesized as described above. Polymers were repurified by three cycles of the following process:

Polymer was dissolved in chloroform, precipitated with 5 volumes of hexane, the solvents was removed, and the precipitate was washed with diethyl ether. Copolymers were then ground to a fine powder under liquid nitrogen, lyophilized overnight, and stored under N_2 at -20°C until use.

CHP PLAMs

PLAMs containing 10% and 20% L-cis-hydroxyproline (CHP) by weight of CPP:SA (20:80) copolymer were produced using the hot melt procedure, as follows:

Dry CHP is added to copolymer and mixed by both vortex and manual stirring with a spatula. The mixture is then transferred to a 1 cc syringe, heated for 10 to 15 minutes at 116 ± 2°C until the polymer becomes molten but CHP remains solid with its crystals widely dispersed throughout the polymer. The mixture is then injected into Teflon® tubing. After the PLAM solidifies for 1 h, the PLAM in Teflon® tubing is cut into cylindrical pellets. The pellets are sterilized by gamma irradiation for 1 h and stored sealed at -20°C until use.

All CHP PLAMs were synthesized using Teflon® tubing (3.1 ± 0.2 mm diameter, denoted "regular bore"). These pellets were cut 1 cm in length and weighed approximately 100 mg. Group 1 animals were implanted with one 10% CHP PLAM pellet on the experimental side. Group 2 animals were implanted with one 20% CHP PLAM pellet on the

experimental side and another on the control side.

The protocols and results are shown in Table 3.

Table 3. Description of Groups.

Group number	Experimental side	Control side
1	1) 10% CHP PLAM 2) 20% bupivacaine PLAM	Sham
2	1) 20% CHP PLAM 2) 20% bupivacaine PLAM	20% CHP PLAM
3a	20% bupivacaine PLAM	Sham
3b	20% bupivacaine PLAM	Sham
4	bupivacaine PLAM	Control PLAM
5	Id-DMS/bupivacaine PLAM	Control PLAM
6	hd-DMS/bupivacaine PLAM	Sham
7	hd-DMS PLAM	Control PLAM

Bupivacaine PLAMs

PLAMs containing 20% crystalline bupivacaine-HCL by weight of CPP:SA 20:80 copolymer were synthesized via the hot melt procedure described above for CHP PLAMs.

Two different-sized diameter Teflon® tubing were used: regular bore (3.1 ± 0.2 mm) and large bore (4.9 ± 0.3 mm). Regular bore pellets were cut 1 cm in length and weighed approximately 100 mg. Large bore pellets were cut 0.5 mm in length and weighed approximately 130 mg. Groups 1, 2 and 3a/3b animals were implanted with 3 regular bore bupivacaine pellets on the experimental side. Group 4 animals were implanted with 3 large bore bupivacaine pellets on the experimental side.

DMS/Bupivacaine PLAMs

PLAMs incorporated both bupivacaine and dexamethasone (DMS) were synthesized via the hot melt procedure described for CHP PLAMs with some differences in initial preparations.

A uniform mixture of DMS and bupivacaine was formed by combining DMS dissolved in 95% ethanol with bupivacaine dissolved in 95% ethanol. The solution was air-dried under the hood at room temperature until the ethanol evaporated and left behind a well-dispersed mixture of dry crystalline DMS and bupivacaine. The crystalline mixture was pulverized under mortar and pestle and combined with copolymer. The rest of the procedures followed those described for CHP PLAMs. All DMS/bupivacaine PLAMs were synthesized using large bore Teflon® tubing.

Two different dosage sets of DMS/bupivacaine PLAMs were produced: high dose (hd) DMS and low dose (ld) DMS. Hd-DMS/bupivacaine PLAMs contained approximately 60 μg DMS per pellet. Ld-DMS/bupivacaine PLAMs contained approximately 15 μg per pellet. Both sets contained 20% bupivacaine by weight. Group 5 animals were implanted with 3 hd-DMS/bupivacaine PLAM pellets on the experimental side. Group 6 animals were implanted with 3 ld-DMS/bupivacaine PLAM pellets on the experimental side. The protocols and results are shown in Table 4.

Table 4. Classification of Capsules

Group #	Type of Side	PLAM Type	No capsule	Diffuse capsule	Laminar capsule
1	experimental	10% CHP+ bup			4
3b	experimental	bupivacaine			4
4	experimental	bupivacaine			6
4	control	control			6
5	control	control		1	4
7	control	control		3	2
5	experimental	ld-DMS/bup	5		
6	experimental	hd-DMS/bup	5		
7	experimental	hd-DMS	5		

DMS PLAMs

PLAMs containing DMS were synthesized via the hot melt procedure described for CHP PLAMs with some differences in initial preparation, as follows.

A uniform mixture of DMS and copolymer was produced by combining DMS dissolved in chloroform with copolymer dissolved in chloroform. The mixture was air-dried under the hood at room temperature until the chloroform evaporated and left behind a dry well-dispersed mass of DMS and copolymer. The dry mixture was pulverized under mortar and pestle and transferred to syringe. The rest of the procedure followed those described for CHP PLAMs. All DMS PLAMs were synthesized using large bore Teflon® tubing. Group 7 animals were implanted with 3 DMS PLAM pellets on the experimental side.

Control PLAMs

Control PLAMs were synthesized via the hot melt procedure described for CHP PLAMs. Control PLAMs contained only CPP:SA (20:80) copolymer and all pellets were synthesized with large bore Teflon® tubing. Groups 6 and 7 animals were

implanted with 3 control PLAM pellets on the control side.

In Vitro Release of Dexamethasone

Tritium labeled dexamethasone (^{3}H-DMS) was purchased from New England Nuclear Corporation (Boston, MA). An aliquot consisting of 10^7 counts was added to a mixture of 200 µg unlabelled DMS and 190 mg bupivacaine dissolved in 95% ethanol. This solution was air-dried under the hood at room temperature until the ethanol evaporated and left behind a well-dispersed mixture of dry crystalline ^{3}H-labelled DMS, unlabelled DMS and bupivacaine. This dry crystalline mixture was pulverized under mortar and pestle and combined with 650 mg CPP:SA (20:80) copolymer. The rest of the procedure followed those described for CHP PLAMs. All ^{3}H-DMS/unlabelled DMS/bupivacaine PLAMs were synthesized using large bore Teflon® tubing. Each pellet was placed in 5 mL of sterile 1X PBS (phosphate-buffered saline) containing 1% sodium azide and incubated at 37°C. The incubated 1X PBS media was removed and stored at -20°C, and replaced with 5 ml of fresh sterile 1X PBS at 2h, 6 h and 24 h time points and then once daily thereafter for 3 weeks. The ^{3}H released was counted using a liquid scintillation counter (Rackbeta 1214).

Behavioral Testing

Male Sprague-Dawley rats housed in groups of 4 were habituated to a hotplate of 56°C both before and after surgery. They were tested between 10 am and 12 pm daily and allowed to adjust to their surroundings in a quiet room at 22 ± 1°C for at least 30 minutes before testing. The rat was wrapped in a towel from the waist up for visual obstruction and hinderance of upper body motion. Held in the experimenter's hand, the animal's hindpaw was placed on the hotplate and latencies

recorded, starting on contact and ceasing with withdrawal from hotplate, via a foot-switch connected to a computer. If latencies exceeded 12 seconds, the rat's hindpaw was removed to prevent injury. No rats were observed to have inflammation or blisters. Rats were tested for at least two weeks prior to surgery to achieve a consistent baseline latency, and testing continued for two weeks after surgery to confirm complete recovery from sensory blockade.

Motor blockade was rated on a 4-point scale. Animals with a motor block of 4 had a clubbed hindpaw and usually dragged their affected leg when walking. Motor block 3 animals walked normally but had toes that failed to splay when the animal was lifted. Animals with motor block of 2 showed toes that splayed but not as fully as normal or motor block 1 animals.

To better assess intensity of sensory block, hot plate latencies were subdivided into 4 classes: (1) maximum block intensity (MBI), when latency = 12 sec, the maximum allowable time the rat's foot can remain on the hot plate before it is manually removed by the experimenter to prevent injury, (2) dense block, when latency = 7-11, 3) partial block, when latency = 4-7 sec, and 4) no block, when latency was less than 4 sec.

Surgery

All animals were anesthetized with 3.5%-4.0% halothane in oxygen and maintained with 1.5%-2.0% halothane. Anesthesia was achieved within 3-5 minutes post induction. Animals were tested by pinching of tailbase and pawpads to confirm the anesthetic state. The thigh area was shaved and an incision was made directly below the greater trochanter. The hamstrings were gently divided by blunt dissection to expose the sciatic nerve. PLAM

pellets were placed adjacent to the sciatic nerve under direct vision in the fascial plane deep to the hamstrings and the site was irrigated with 0.5 cc of antibiotic solution (5000 units/mL penicillin G sodium and 5000 ug/mL streptomycin sulfate) to prevent infection. The most superficial facial layer was closed with a single suture. The edges of the outer skin were approximated and closed with one to two surgical staples.

For all rats, drug-containing PLAMS were implanted on the experimental side. The control (contralateral) side varied among the groups. Group 1 used 10% CHP PLAMs on the control side to compare the effects of bupivacaine and CHP PLAMs vs. CHP PLAMs alone. Groups 2, 3a/3b and 5 received sham operations on the control side to compare the effects of drug vs. both drug-free and PLAM-free states. Sham operations consisted of exposing the sciatic nerve, irrigation of the site with antibiotic solution, and closure of the surgical site without implantation of any PLAM pellets. Groups 4, 6 and 7 used control PLAMs on the control side to compare the effects of drug vs. drug-free PLAM states.

Necropsy

All groups, except groups 2 and 3a, were sacrificed at two weeks by CO_2 asphyxiation. Groups 2 and 3a were sacrificed five days post-surgery. Groups 4, 5 and 6 were given cardiac punctures and blood samples were taken for ACTH and cortisol assays. For autopsy, the skin of the dorsal thigh was removed. A midline transverse cut was made through each successive layer of hamstring muscle to locate the site of encapsulation, if any, and preserve its integrity and architecture. The capsule was excised by blunt dissection and placed in 10% formalin. A 3 cm segment of the sciatic

nerve was removed from its exit point at the greater sciatic foramen to its branching point above the dorsal aspect of the knee joint. For light microscopy, a segment was fixed in 10% buffered formalin.

Statistics

All data were analyzed using repeated measure ANOVA, post-hoc paired t-tests, Fisher exact tests and Wilcoxon rank sum tests where deemed appropriate.

Histology

Nerves: For evaluation of sciatic nerves, cross-sections were processed, embedded in paraffin and sectioned at 2 μm and stained with hematoxylin eosin. 5-10 sections were studied via light microscopy by a pathologist in a blinded manner. Each cross-section was evaluated for (1) epineural inflammation, (2) epineural fibrosis, and (3) subperineural fibroblasts. Each parameter was rated on a severity scale of 0-4. A score of 0 = no change, 1 = mild, 2 = moderate, 3 = moderate-severe and 4 = severe.

Capsules: Encapsulation was evaluated by gross examination at the time of dissection and through photographs by a blinded observer. This evaluation was divided into 3 categories. The first type was characterized by no true capsule. It involved nonspecific, unorganized inflammatory debris surrounding the implantation site. The other two capsule types were classified according to the manner of Ksander, et al. (G.A. Ksander, L.M. Vistnes and D.C. Fogerty, "Experimental effects on surrounding fibrous capsule formation from placing steroid in a silicone bag-gel prosthesis before implantation," Plast. & Reconstr. Surg., 62, 873-883 (1978)). The second type was characterized by flimsiness, an ability to be

easily deformed and torn, and an irregular dull surface of white to gray color. This type was designated as a diffuse capsule. The third type was characterized by toughness, resistance to deformation by handling and tearing at excision, and a smooth glossy inner surface of yellowish-brown to clear translucence. This type was designated as a laminar capsule. It was a true histological capsule with highly organized, fibrous walls enclosing the implanted pellets, completely separating it from immediate surrounding tissue. A severity scale of 0-4, similar to that described above, was used to rank the degree of inflammation of the perineural fascia and muscle fascia.

Cross-sections of formalin-fixed capsules were examined by light microscopy and rated on a severity scale from 0-4, specifically looking at (1) thickness of capsule wall, (2) proportion of PMN's in relation to other inflammatory cells, (3) proportion of lymphocytes to other inflammatory cells, (4) proportion of plasma cells to other inflammatory cells, (5) proportion of foreign body giant cells to other inflammatory cells, (6) proportion of immature fibroblasts to mature fibroblasts, and (7) extent of collagen deposition in the capsule wall.

RESULTS

In Vitro Release of DMS

The release of DMS from PLAM was nearly linear for the first 8 days and eventually reached a plateau by Day 21. Approximately 60% of DMS was released from PLAM by Days 7-8 and by Day 21, 97% of DMS was released (Figure 1).

Histology

Capsules

Dexamethasone prevented capsule formation in all groups whose experimental side received DMS-

containing PLAM pellets (Groups 5, 6, and 7). In contrast, CHP did not prevent encapsulation. [see Table 3] All groups treated with CHP (Groups 1 and 2) formed capsules around implants by the time of dissection. Groups implanted with bupivacaine PLAMs (Group 3b and 4) and no additive (DMS or CHP) developed capsules around implants. Groups which received control PLAMs (Groups 4, 5 and 7) also formed capsules around implants. DMS-treated sides were significantly different from contralateral control sides implanted with drug-free PLAMs (Group 5 and 7, $p<.0001$). They were also statistically different from sides receiving CHP-(Group 1, $p = .0003$) and/or bupivacaine-containing PLAM pellets (Group 3b and 4, $p<.0001$). Capsules formed from drug-free PLAMs (control PLAMs) were histologically indistinguishable from those that resulted from drug-containing PLAMs (CHP and bupivacaine). This was determined through examination of a variety of inflammatory factors. Capsules produced from drug-containing PLAMs were statistically insignificant from drug-free PLAMs in terms of (1) capsule thickness, (2) acute PMNs, (3) foreign body cells, (4) collagen content, (5) immature fibroblasts, and (6) mature fibroblasts. Two categories produced marginal statistical significance ($p = 0.0461$): chronic round cells and plasma cells. This implied that drug-containing PLAMs may produce slightly more inflammation of the chronic inflammatory type.

Nerves

All groups showed no statistical significance between experimental and control sides in all three inflammatory factors examined: (1) epineural inflammation, (2) epineural fibrosis, and (3) perineural fibroblasts. Comparisons of experimental sides receiving CHP and bupivacaine vs. bupivacaine alone (Group 1 versus Group 3b and

Group 2 versus Group 3a) showed no statistical significance. No difference in neural inflammation was found comparing groups receiving 10% CHP vs. 20% CHP (Group 1 versus Group 2) and groups sacrificed Day 5 versus Day 14 (Group 3a versus 3b). Comparison of experimental sides receiving DMS/bupivacaine versus bupivacaine alone (Group 5 versus Group 4 and Group 6 versus Group 4) showed no difference. No difference was also found comparing groups implanted with bupivacaine alone versus DMS alone (Group 4 versus Group 7) and hd-DMS.bupivacaine vs. ld-DMS/bupivacaine (Group 5 versus Group 6). One set, Group 6 versus Group 7, showed statistical significance. Group 6 produced a greater degree of epineural inflammation ($p = .0238$) than Group 7. The other two inflammatory factors, epineural fibrosis and perineural fibroblasts, were statistically insignificant for Group 6 versus Group 7.

Sensory and Motor Blockade Among Animals Treated with DMS and CHP

Group 5 (animals implanted with ld-DMS/bupivacaine PLAMs) had the longest sensory and motor blockade. Sensory blockage lasted for a period of 6-7 days with maximum block intensity (latency = 12 sec) observed on days 1-5 in all animals, as shown by Figure 5. Motor blockade lasted for 6-8 days with the densest motor block seen on day 1-5. All animals returned to baseline on Day 8, as shown by Figure 6a.

Rats implanted with hd-DMS/bupivacaine PLAMs (Group 6) also had sensory block lasting 6-7 days, as shown by Figure 5. However, maximum block intensity was observed only on days 1-2 in all rats. A plateau of dense block (latency = 7-11 sec) was seen on days 3-5. Motor blockade lasted for 3-5 days with the densest motor block occurring on day 1-2, as shown by Figure 6c.

Group 4 animals (control group receiving large bore bupivacaine PLAMs) had sensory blockade lasting 5-6 days, as shown by Figure 5. There were no time points when all animals had maximum block intensity simultaneously. However, dense sensory block (latency = 7-11 sec) was observed on days 1-4 in all animals. Motor blockade lasted 3-6 days with densest block seen on Days 1-2, as shown by Figure 6a.

Group 7 rats, who were implanted with hd-DMS PLAMs, showed no sensory and motor block, and all time points could not be distinguished from baseline.

Group 1, 2 and 3a/3b rats, who were implanted with 10% CHP PLAM plus bupivacaine PLAMs, 20% CHP PLAMs and plus bupivacaine PLAMs, and bupivacaine PLAMs alone, respectively, all displayed similar sensory block durations and intensities. All groups showed sensory block durations of 2-4 days with dense block seen on Day 1 and the majority of rats returning to baseline on Days 2-4, as shown by Figure 7. Motor blockade were similar for Groups 1 and 3a/3b. Duration of motor block lasted for 1-2 days with the densest block observed primarily on day 1. Group 2 had motor blockade lasting for 1-4 days with the densest block also occurring on day 1, as shown by Figures 8a, 8b and 8c. One animal from Group 2 was dropped from the study because it did not recover motor- and sensory-wise. One animal from Group 3a was dropped from the study because it did not recover motorwise, although its sensory functions were intact and it returned to baseline.

Plasma Assays for ACTH and Corticosterone

Plasma assays performed on Groups 5, 6 and 7 animals showed no difference in ACTH and corticosterone levels compared to normal values of

rats taken at the same period of day and under similar stress-level conditions. Prolonged release of dexamethasone, approximately 5-10 μg per day for 2 weeks, did not cause pituitary suppression of ACTH and consequently, did not decrease plasma levels of corticosterone.

Summary of Results

The present study demonstrates that DMS released from biodegradable polymer matrices can prevent encapsulation around polymer implants seen during autopsy at 2 weeks post-implantation. Sensory and motor blockade is profoundly enhanced in animals treated with DMS. Light microscopy studies show that DMS-treated sides have equivalent neural inflammation to sham operations, control PLAMs or bupivacaine PLAMs.

Modifications and variations of the present invention, a biodegradable controlled release device for the prolonged and constant delivery of a local anesthetic agent, will be apparent to those skilled in the art from the foregoing detailed description of the invention. Such modifications and variations are intended to come within the scope of the appended claims.

We claim:

1. A method for sustained regional release of local anesthetic at a site in a patient comprising

administering at the site a local anesthetic incorporated into a device consisting essentially of a biocompatible polymer degrading at least fifty percent in less than six months following implantation into the patient, wherein the local anesthetic is present in a concentration effective to achieve pain relief at the site, and wherein the device does not elicit a significant inflammatory response at the site.

2. The method of claim 1 wherein the polymer is selected from the group consisting of polyanhydrides, copolymers of lactic acid and glycolic acid, polyorthoesters, proteins, and polysaccharides degrading at least fifty percent in less than six months following implantation into the patient.

3. The method of claim 1 wherein the device is in a form selected from the group consisting of slabs, beads, pellets, microparticles, microspheres, microcapsules, and pastes.

4. The method of claim 1 wherein the anesthetic is selected form the group consisting of bupivacaine, dibucaine, etidocaine, tetracaine, lidocaine, xylocaine and salts thereof.

5. The method of claim 1 wherein the anesthetic is incorporated into the polymer at a percent loading of 0.1% to 70% by weight.

6. The method of claim 5 wherein the anesthetic is incorporated into the polymer at a percent loading of 5% to 50% by weight.

7. The method of claim 1 wherein the device is formed by a method yielding a uniform dispersion of anesthetic within the polymer.

8. The method of claim 1 wherein the device further comprises an antiinflammatory in a concentration effective to inhibit inflammation following implantation into a patient.

9. The method of claim 1 wherein the polymer does not elicit inflammation following implantation into a patient.

10. The method of claim 1 further comprising administering the device by injection.

11. A device for sustained regional release of local anesthetic at a site in a patient comprising

a local anesthetic incorporated into a device consisting essentially of a biocompatible polymer degrading at least fifty percent in less than six months following implantation into the patient, wherein the local anesthetic is present in a concentration effective to achieve pain relief at the site, and wherein the device does not elicit a significant inflammatory response at the site.

12. The device of claim 11 wherein the polymer is selected from the group consisting of polyanhydrides, copolymers of lactic acid and glycolic acid, polyorthoesters, proteins, and polysaccharides degrading at least fifty percent in less than six months following implantation into the patient.

13. The device of claim 11 wherein the device is in a form selected from the group consisting of slabs, beads, pellets, microparticles, microspheres, microcapsules, and pastes.

14. The device of claim 11 wherein the anesthetic is selected form the group consisting of

bupivacaine, dibucaine, etidocaine, tetracaine, lidocaine, xylocaine and salts thereof.

15. The device of claim 11 wherein the anesthetic is incorporated into the polymer at a percent loading of 0.1% to 70%.

16. The device of claim 15 wherein the anesthetic is incorporated into the polymer at a percent loading of 5% to 50%.

17. The device of claim 11 wherein the device is formed by a method yielding a uniform dispersion of anesthetic within the polymer.

18. The device of claim 11 further comprising an antiinflammatory in a concentration effective to inhibit inflammation following implantation into a patient.

19. The device of claim 11 wherein the polymer does not elicit inflammation following implantation into a patient.

20. The device of claim 11 further comprising a pharmaceutically acceptable carrier for administering the device by injection.

21. The device of claim 11 wherein the polymer incorporating the local anesthetic is coated with a material preventing inflammation as a result of implantation of the polymer.

22. A device for sustained linear release of a drug at a site in a patient comprising an antiinflammatory in combination with the drug to be released both incorporated into a biodegradable, biocompatible polymeric device, wherein the antiinflammatory in a concentration effective to inhibit inflammation following implantation of the device into a patient.

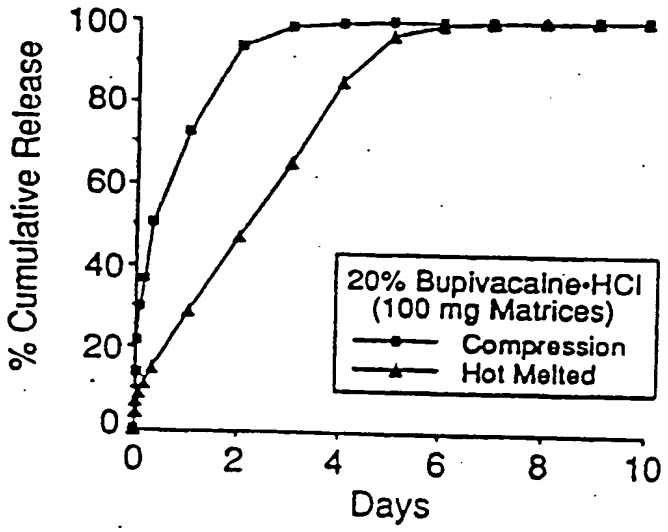

% Cumulative Release
100
80
60
40
20
0
0
2
4
6
8
10
Days
20% Bupivacaine·HCl
(100 mg Matrices)
Compression
Hot Melted

FIG. 1a

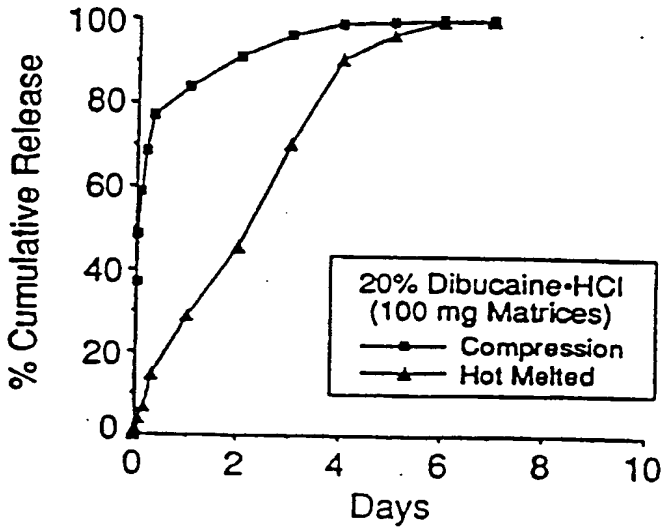

% Cumulative Release
100
80
60
40
20
0
0
2
4
6
8
10
Days
20% Dibucaine·HCl
(100 mg Matrices)
Compression
Hot Melted

FIG. 1b

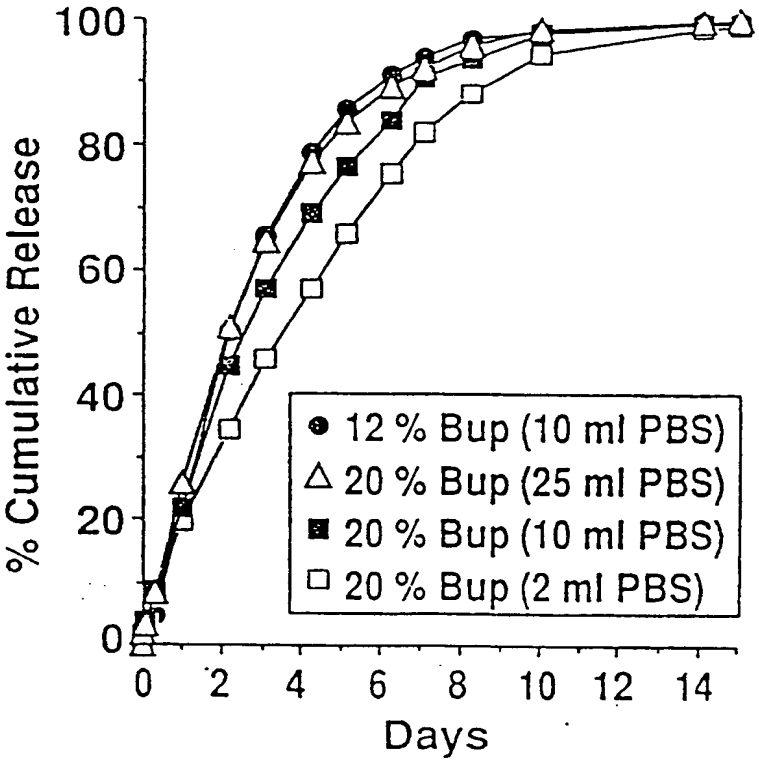

100
80
60
40
20
0
% Cumulative Release
0
2
4
6
8
10
12
14
Days
12 % Bup (10 ml PBS)
20 % Bup (25 ml PBS)
20 % Bup (10 ml PBS)
20 % Bup (2 ml PBS)

FIG. 2

A

FIG. 3a Group 1

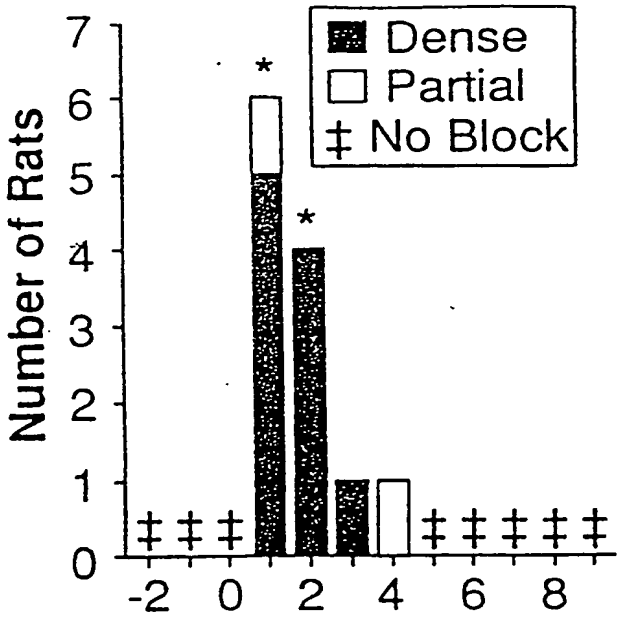
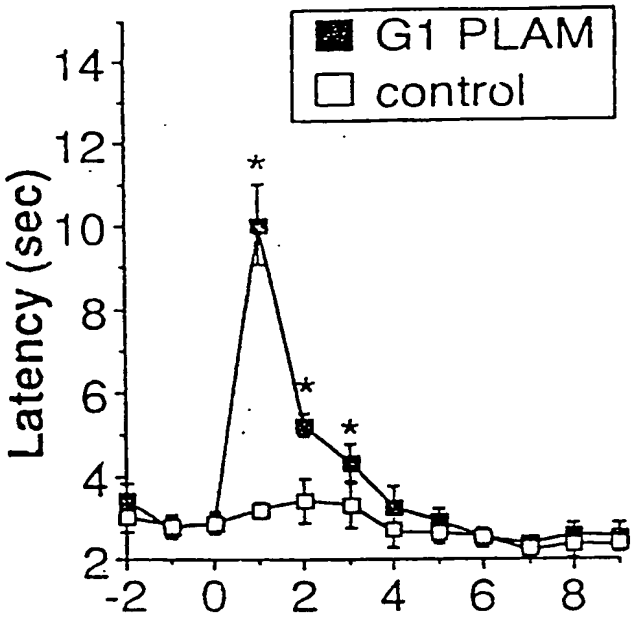


FIG. 3b



B

FIG. 3c Group 2

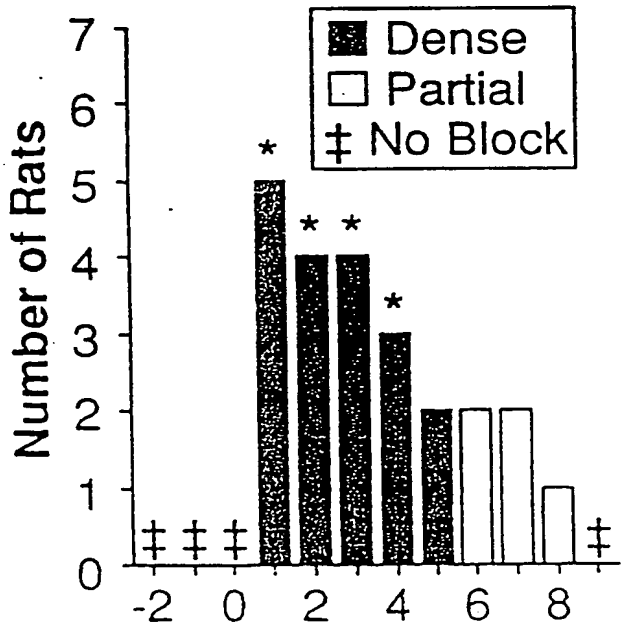
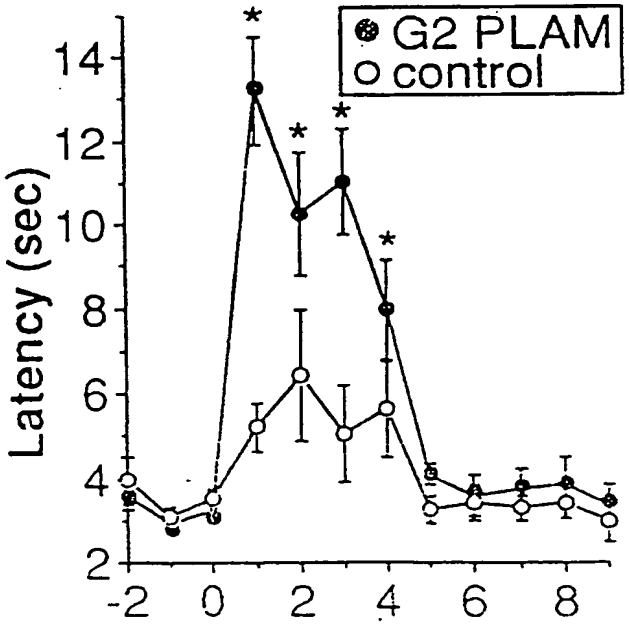


FIG. 3d



Days Post-Implantation

C

FIG. 3e

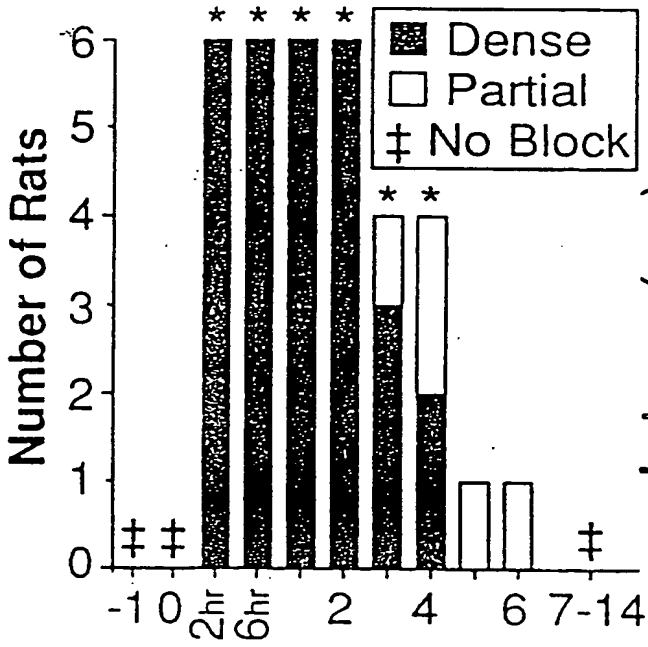
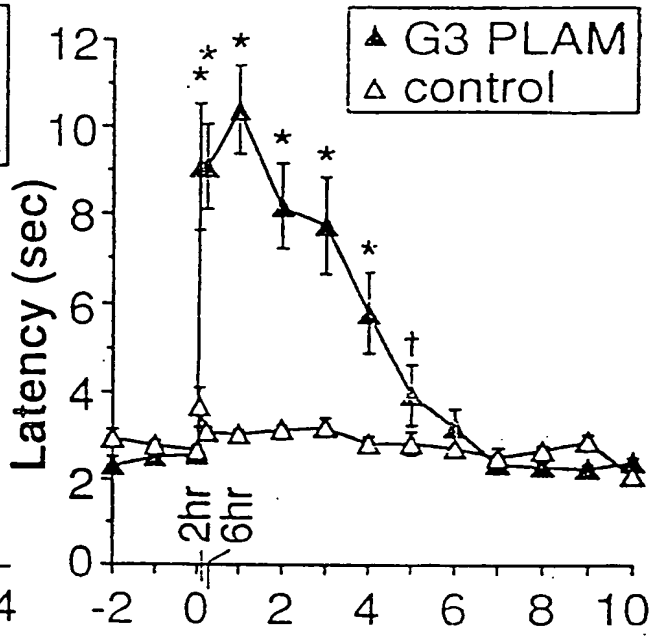


FIG. 3f



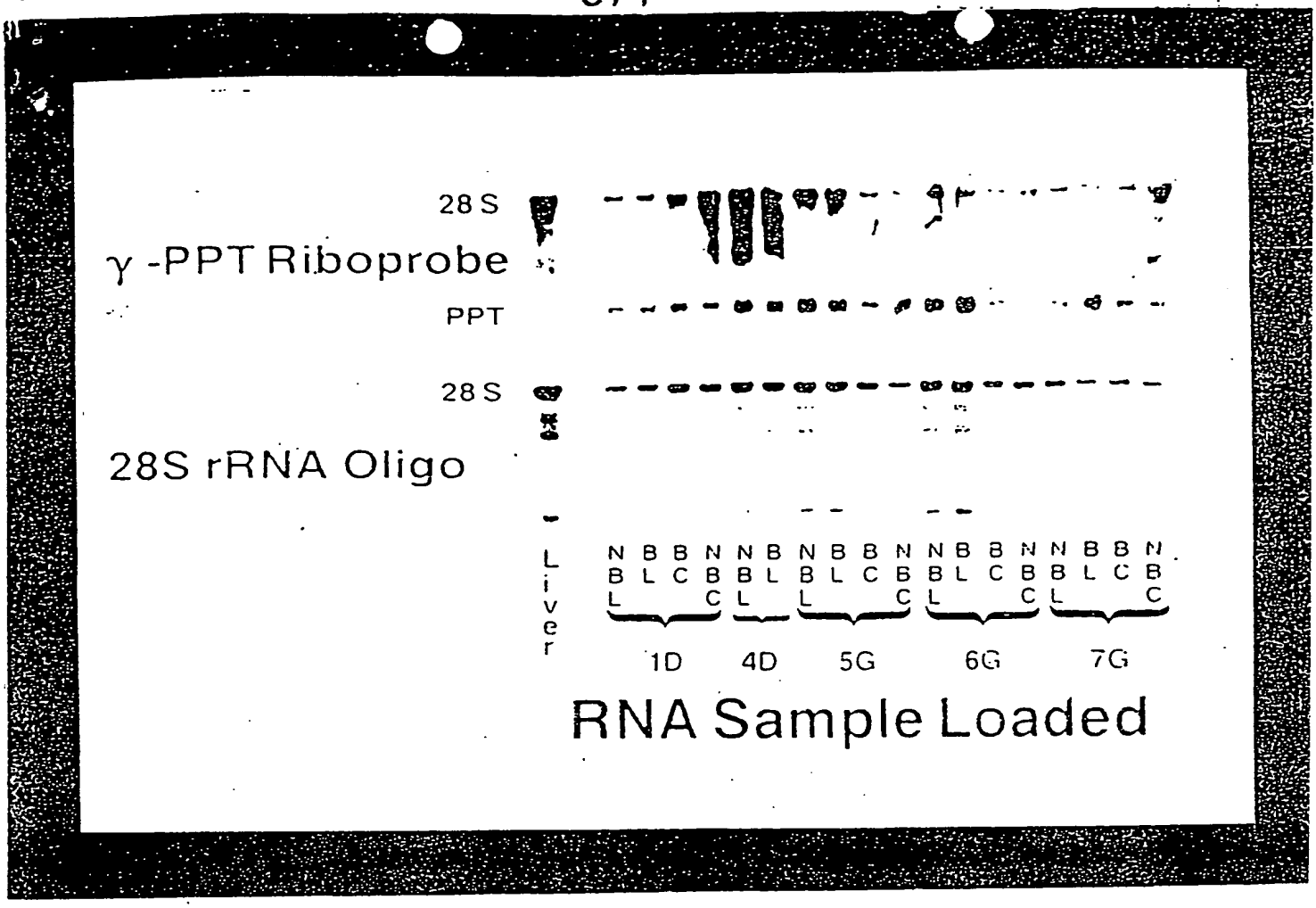

28S
γ-PPT Riboprobe
PPT
28S
28S rRNA Oligo
Liver
N B L
B L C
B C
N B C
N B L
B L
N B L
B L C
B C
N B C
N B L
B L C
B C
N B C
N B L
B L C
B C
N B C
1D
4D
5G
6G
7G
RNA Sample Loaded

FIG. 4

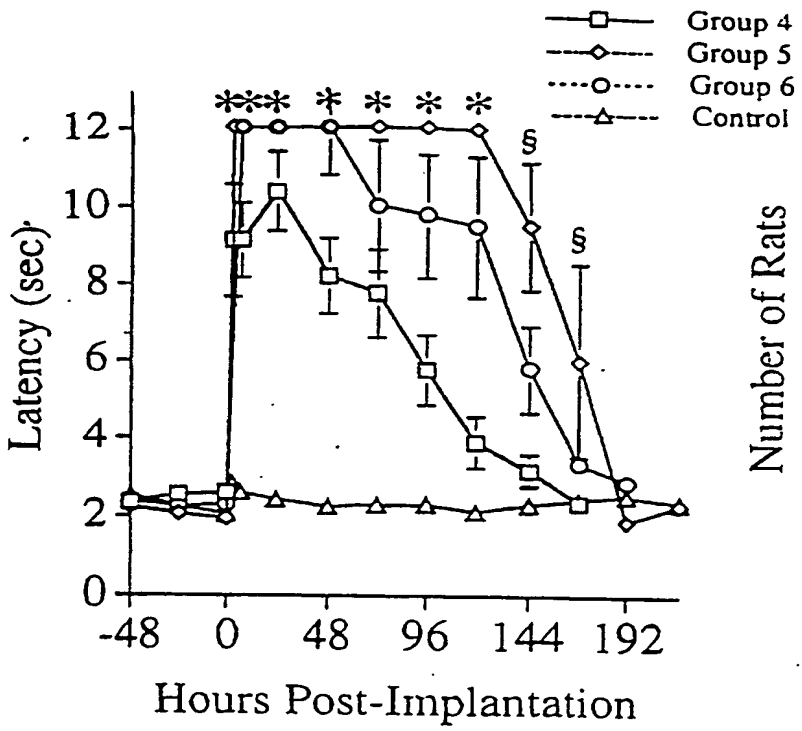


FIG. 5

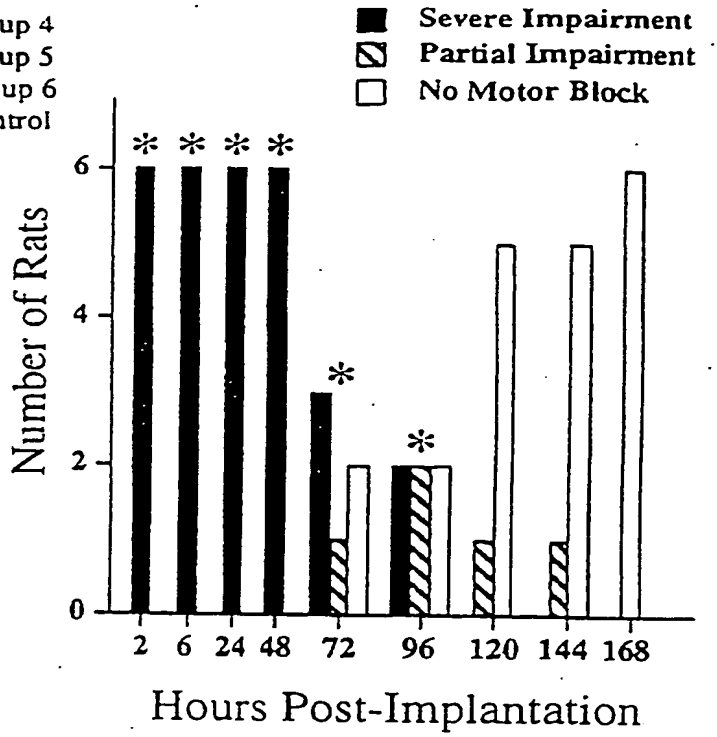


FIG. 6a

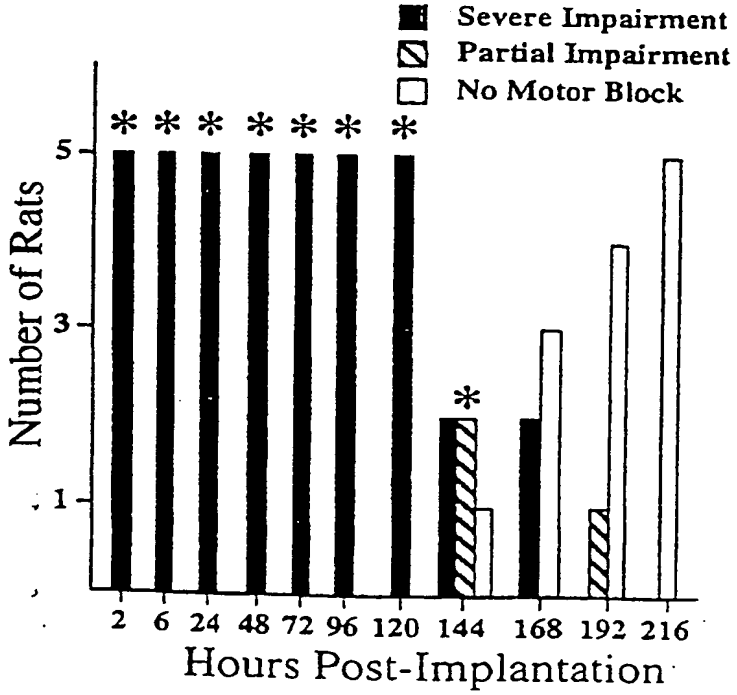


FIG. 6b

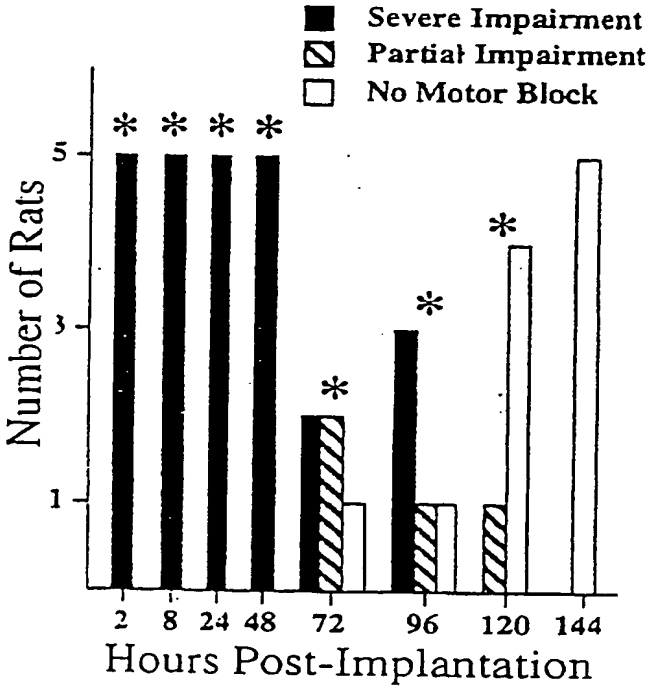


FIG. 6c

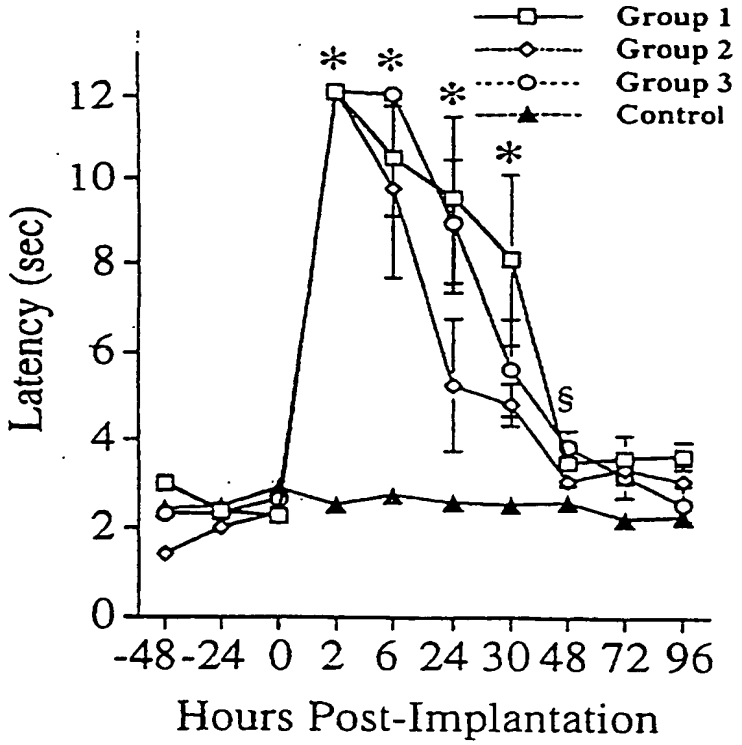


FIG. 7

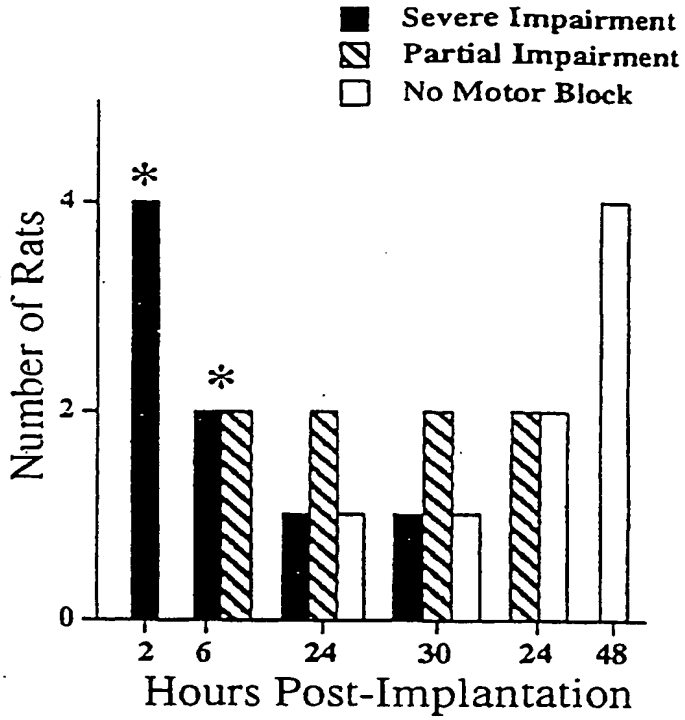


FIG. 8a

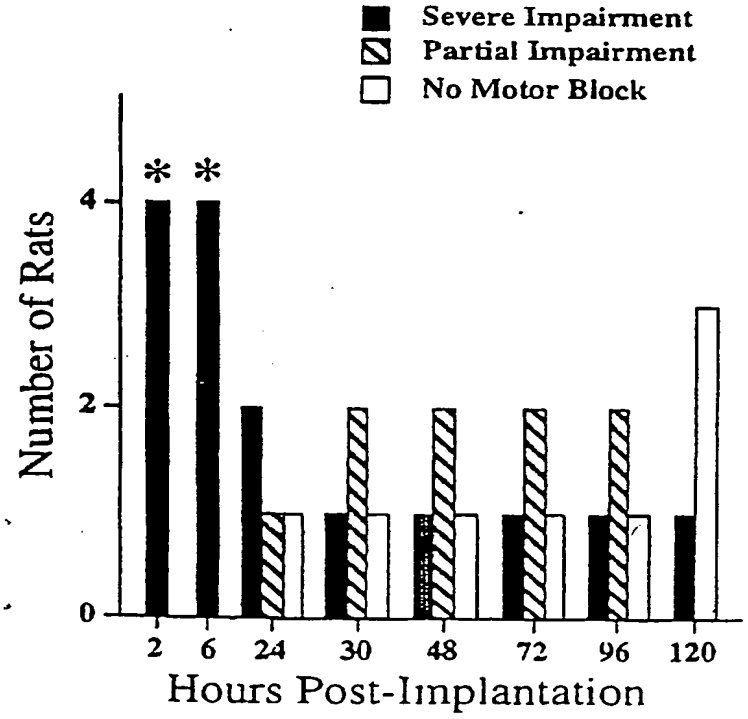


FIG. 8b

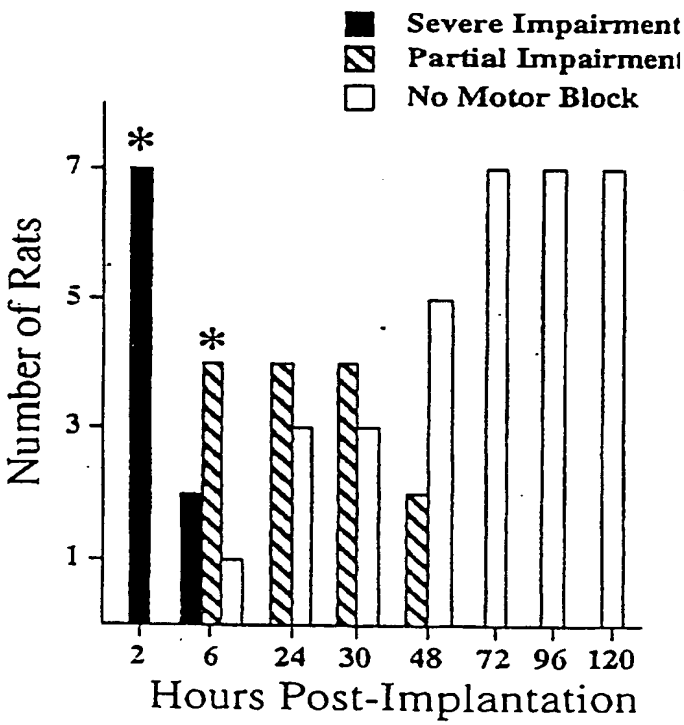


FIG. 8c

INTERNATIONAL SEARCH REPORT

Inte. nal Application No
PCT/US 93/08568

A. CLASSIFICATION OF SUBJECT MATTER
IPC 5 A61K9/20 A61K9/16

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC 5 A61K

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	EP,A,0 244 118 (PHARMETRIX CORPORATION) 4 November 1987 see the whole document ---	1-22
X	WO,A,92 07555 (ALZA CORPORATION) 14 May 1992 see the whole document -----	1-22

☐ Further documents are listed in the continuation of box C.

☒ Patent family members are listed in annex.

* Special categories of cited documents :

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier document but published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art.

"&" document member of the same patent family

Date of the actual completion of the international search
19 November 1993

Date of mailing of the international search report
15. 12. 93

Name and mailing address of the ISA
European Patent Office, P.B. 5818 Patentlaan 2
NL - 2280 HV Rijswijk
Tel. (+31-70) 340-2040, Tx. 31 651 epo nl,
Fax (+31-70) 340-3016

Authorized officer
VENTURA AMAT, A

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US93/08568

Box I Observations where certain claims were found unsearchable (Continuation of item 1 of first sheet)

This international search report has not been established in respect of certain claims under Article 17(2)(a) for the following reasons:

1. [X] Claims Nos.:
because they relate to subject matter not required to be searched by this Authority, namely:
Remark: Although claims 1-10 are directed to a method of treatment of the human body, the search has been carried out and based on the alleged effects of the composition.

2. [ ] Claims Nos.:
because they relate to parts of the international application that do not comply with the prescribed requirements to such an extent that no meaningful international search can be carried out, specifically:

3. [ ] Claims Nos.:
because they are dependent claims and are not drafted in accordance with the second and third sentences of Rule 6.4(a).

Box II Observations where unity of invention is lacking (Continuation of item 2 of first sheet)

This International Searching Authority found multiple inventions in this international application, as follows:

1. [ ] As all required additional search fees were timely paid by the applicant, this international search report covers all searchable claims.

2. [ ] As all searchable claims could be searches without effort justifying an additional fee, this Authority did not invite payment of any additional fee.

3. [ ] As only some of the required additional search fees were timely paid by the applicant, this international search report covers only those claims for which fees were paid, specifically claims Nos.:

4. [ ] No required additional search fees were timely paid by the applicant. Consequently, this international search report is restricted to the invention first mentioned in the claims; it is covered by claims Nos.:

Remark on Protest

[ ] The additional search fees were accompanied by the applicant's protest.

[ ] No protest accompanied the payment of additional search fees.

INTERNATIONAL SEARCH REPORT

Information on patent family members

Inte. ...nal Application No
PCT/US 93/08568

Patent document cited in search report	Publication date	Patent family member(s)		Publication date
EP-A-0244118	04-11-87	US-A-	4780320	25-10-88
		AU-B-	614061	22-08-91
		AU-A-	7211287	05-11-87
		JP-A-	63027422	05-02-88
		US-A-	4919939	24-04-90
WO-A-9207555	14-05-92	AU-A-	8935591	26-05-92